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THE CLAY-LIKE MECHANICS MODEL OF CYLINDRICAL LITHIUM-ION BATTERY CELLS UNDER RADIAL COMPRESSION

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Abstract

A simple load case was chosen to reveal the essential mechanics properties of cylindrical lithium-ion battery and it was found that its mechanics characteristic is clay-like, according to the plastic flow rule. Then, a linear equation was proposed to describe the nonlinear constitutive behavior of cylindrical lithium-ion battery, which will lay a foundation for constructing the system of battery mechanics, according to the mechanics characteristic of clay.

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Keywords: lithium-ion battery, flow rule, clay-like, constitutive equation

1. INTRODUCTION

The unique characteristics of electric vehicle make it to be an effective solution to the problem of energy, environmental and climate change in the field of urban traffic. However, with the rapid popularization of electric vehicle, fewer researches were carried out on mechanics characteristic of battery in recent years, which is very important for dealing with the multi-field coupling problem of thermal runaway caused by stress during traffic accident, compared with heat management, electrochemistry and so on. Better knowing of the mechanics characteristic of battery could provide mechanical parameters for the design of battery and battery box, decrease the risk of short circuits and the following thermal or fire under extreme loading.

The mechanical characteristic of the whole battery cell under different loading conditions were investigated by several authors. Wierzbicki et al developed a hybrid experimental/analytical approach for extracting the average mechanical properties of cylindrical Li-ion cells and used principle of virtual work to estimate the stress-strain relation for the cell crushed between two flat plates. They developed a finite element model to predict kinematic of the cell during two different load cases and found the resistance of the cell comes primarily from the jellyroll. [1]. Greve et al performed a quasi-static mechanical abuse test program on cylindrical lithium ion battery cells at a state of charge of 0% and established a macro-mechanical finite element crash simulation model for the cell housing and the jelly

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roll. They applied the classical stress-based criterion after Mohr and Coulomb to predict fracture and the initiation of an internal short circuit of the jelly roll. [2]. Gilaki et al established a model to predict mechanical response of cylindrical lithium-ion battery cells subjected to impact testing and they found the feasibility of using explicit finite element code for accurate modeling of impact on one cell[3].

However, the model in the reference [2] is too complicated, which needs a lot of parameters. The model in the reference [1] and [3] need fewer parameters at the cost of a little loss of accuracy. In this investigation, it was found that the mechanics characteristic of cylindrical lithium-ion battery is clay-like and the plastic constitutive equation of cylindrical lithium-ion battery was proposed, which ensures the precision and needs few and easily obtained parameters, referring to the mechanics characteristic of clay. Our model could be used to predict the deformation behavior of cell under various loading conditions, the inside stress state of cell during deformation and provides parameters for improving the mechanical safety of lithium-ion batteries.

2. THE MECHANICS CHARACTERISTIC OF THE LITHIUM-ION BATTERY

2.1. The clay-like mechanics characteristic of lithium-ion battery

In general, the mechanics properties of material are essential. For simplifying the mathematical operation in the process of the establishment of constitutive equation, cylindrical lithium-ion battery under radial compression between two flat plates was chosen as the inferential model. See Figure 1.

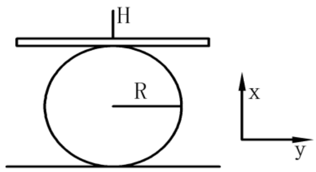

Fig. 1. Compression of a cylinder cell between two flat plates

Firstly, some simplification about the conditions of stress and strain during deformation would be made. The loading undertaken by cell is always a simple unidirectional (radial) compression during deformation, so, the shear forces inside the cell are so small that $\tau_{xy} = 0,\ \tau_{yz} = 0,\ \tau_{zx} = 0$. At the same time, the length of cell in *z* direction is constant, $\varepsilon_z = 0$ and according to the delamination of the layers in *y* direction in the semicircular zones [1], $\sigma_y = 0$.

According to the flow rule:

$$d\varepsilon_z^p = d\lambda\, \partial f / \partial \sigma_z \tag{1}$$

where λ is plastic ratio, f is the plastic potential function, which could be written in the form, $f\left(\sigma_x, \sigma_y, \sigma_z, \tau_{xy}, \tau_{yz}, \tau_{zx}\right)$. Under this load case, the formula could be simplified into $f(\sigma_x, \sigma_y)$.

Because $\varepsilon_z = 0$, $d\lambda \neq 0$, σ_z and σ_x are the same unit and $\sigma_x = 0$, $\sigma_z = 0$ at original state:

$$\sigma_z = a\sigma_x \tag{2}$$

where *a* is non-negative constant. By substituting $\sigma_x,\ \sigma_y = 0,\ \sigma_z = a\sigma_x,\ \tau_{xy} = 0,\ \tau_{yz} = 0,\ \tau_{zx} = 0$, into average principal stress p and generalized shear stress q in clay mechanics:

$$p = (\sigma_1 + \sigma_2 + \sigma_3) \div 3 \tag{3}$$

$$q = \sqrt[2]{[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2] \div 2} \tag{4}$$

So lithium-ion battery has linear relationship on the $p - q$ plane. There are common linear relationships on the $p - q$ plane and the $v - ln\, p$ plane which were confirmed by a large number of experimental data existing in remolded and saturated clay, which is normally consolidated.

When battery was in the state of deformation, the contribution to resisting the deformation is mainly from the jellyroll. Besides, due to the relatively large Young's modulus of the current collector foils, the jelly roll deformation is mainly taking place in the nonmetallic porous particle coatings of the jelly roll [2]. So mechanics characteristic of cylindrical lithium-ion battery is similar with clay to a great extent, especially in the case of compression.

2.2. Constitutive equation of the lithium-ion battery

It is possible that lithium-ion battery also has linear relationship on the $v - ln\, p$ plane, since it has linear relationship on the $p - q$ plane. Under above load case, the volumetric strain of cell has a relationship with its average stain. In other words, it is possible that lithium-ion battery has linear relationship on the $\varepsilon_{av} - ln\, p$ plane:

$$\varepsilon_{av} = m\, ln\, p + n \tag{5}$$

where m, n, are constant. The simplified process of deformation is shown in Figure 2.

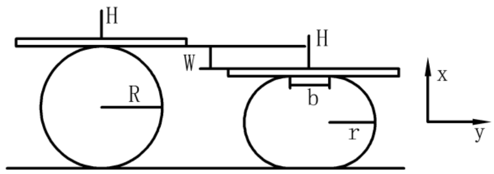

Fig. 2. The simplified process of deformation

The average stress and strain are:

$$\varepsilon_{av} = w/2R \tag{6}$$

$$\sigma_{av} = p = 2H/\pi L w \tag{7}$$

where L is the length of cell in z direction, w is the vertical displacement of the plate, R is the original radius of the cylinder Lithium-ion battery cell, H refers to the function of crush distance. According to the reference [3], the load-displacement curve can be precisely interpolated by the third order polynomial function.

Because:

$$d\sigma_{av}/\sigma_{av} = 2\, dw/w \tag{8}$$

$$d\varepsilon_{av}/\varepsilon_{av} = dw/w \tag{9}$$

There is a linear relationship on the $ln\, \sigma_{av} - ln\, \varepsilon_{av}$ plane. A further assumption was made that there is a linear relationship on the $ln\, \sigma - ln\, \varepsilon$ plane under any complicated situations. So the constitutive equation:

$$ln\, \sigma_i = A\, ln\, \varepsilon_i^p + B \tag{10}$$

where σ_i and ε_i^p are equivalent stress and strain, *A* and *B* are constant, determined by the properties of battery.

2. VALIDATION

In this section, two constitutive equations were used to validate its accuracy. One of them was deduced by Wierzbicki et al [1] and the other one was deduced by Greve et al [2]. Substitute these parameters into the equations and for $\bar{\varepsilon}_p > 0.02$:

$$\sigma_{av} = 498\varepsilon_{av}^2 \tag{11}$$

$$\bar{\sigma} = 0.8 + 600(\bar{\varepsilon}^p)^{2.7} \tag{12}$$

where $\bar{\sigma}$ and $\bar{\varepsilon}^p$ are the equivalent stress and strain. Because 0.8≪600, above equations could be written in general formula:

$$\bar{\sigma} = K(\bar{\varepsilon}^p)^j \tag{13}$$

where *K*, *j*, are constant. It is obviously that both equations have linear relationships on the $ln\, \sigma_i - ln\, \varepsilon_i^p$ plane. Besides, according to the reference [4], the stress-strain curve obtained from experiment can be fitted to equation (14):

$$\sigma = C\varepsilon^2 \tag{14}$$

where C is constant. So, the constitutive equation in this paper could exactly predict the stress inside battery after deformation and could be applied to engineering practice.

3. CONCLUSION AND DISCUSSION

In this paper, it was found that the mechanics characteristic of cylindrical lithium-ion battery is clay-like and a linear mathematical model was proposed, which could describe the mechanical properties of cells under various loading cases and be used to improve battery design with respect to safety. As we know, the mechanical characteristic of cell is a new field. Since the mechanics characteristic of cylindrical lithium-ion battery is clay-like, we could refer to the developed theory of clay and even the simulation of clay during the research.

But this mathematical model was only suited for the radial direction. So, more researches on the mechanics characteristic of lithium-ion battery will be done and a finite element model will be developed through the constitutive equation to further apply in engineering practices.

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